Renewable and Sustainable Energy Reviews 28 (2013) 588–596

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Methods to determine the dc parameters of solar cells: A critical review

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ARTICLE INFO

Article history:
Received 12 September 2012
Received in revised form
30 July 2013
Accepted 11 August 2013
Available online 3 September 2013

Keywords:
Solar cells parameters
I–V characteristic
One and two diode models

ABSTRACT

This review article critically outlines and discusses the main issues of 34 methods which have been developed and validated over the past 35 years in order to determine with an acceptable accuracy and reliability fundamental parameters of solar cells. This review covers methodologies which deal with current–voltage characteristic (*I–V*) analysis either theoretically through elaborated models and/or treated graphically. Methodologies based on the theoretical analysis of the *I–V* characteristics using the one or two diode model are discussed. The investigation on the *I–V* characteristics is processed via statistical functions, non-linear regression and stochastic models. A second family of methods to determine the solar cell electric parameters comprises the ones which deal with the graphical treatment and analysis of the *I–V* characteristics which are measured at different environmental conditions. To the third family belong the methods which use a mix approach of theoretical analysis of the *I–V* characteristics through modeling on one hand and the graphical analysis of their experimental configuration, on the other. The paper comments on each of the 34 methods and provides pros and cons for the determination of the fundamental electric parameters of solar cells.

Contents

1. Introduction

The main targets in the energy policy and the research priorities and efforts drive towards increasing the efficiency of the renewable energy systems available, and to the design of cost effective technologies.

The production of photovoltaic energy has undergone a sustainable growth rate, with maximum points in the three oil crisis, when the need of alternative types of energy sounds prominent. The objective established by the European Union is that until 2020 the photovoltaic energy represents 12% of the total electric energy production [1].

The determination and knowledge of the influence of solar cells parameters upon their efficiency become crucial for the optimization of fabrication processes and for the scientific research [2]. The possibility to determine the important parameters of the solar cells plays a major role in evaluating the solar cells, in controlling their quality, and also in the fabrication and power performance of reliable solar panels.

The most important parameters of solar cells can be determined by using the current–voltage (*I–V*) characteristic which is shown in Fig. 1 and by analyzing their equivalent circuit [2]. These parameters are: I_{ph} – the photogenerated current, I_{sc} – the short circuit current, V_{oc} – the open circuit voltage, n – the ideality factor of diode, R_s – the series resistance, R_{sh} – the shunt resistance, I_o – the reverse saturation current, P_m – the maximum power, V_m – the voltage at P_m, I_m – the current at P_m, FF – the fill factor and η – the efficiency.

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http://dx.doi.org/10.1016/j.rser.2013.08.017

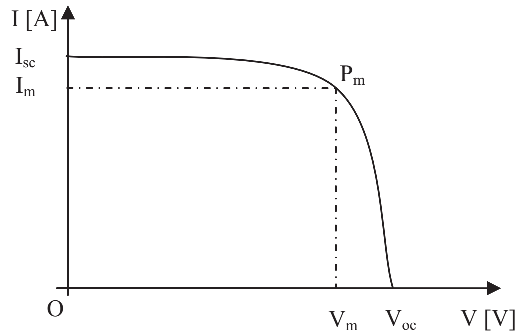


Fig. 1. The *I–V* characteristic for solar cell.

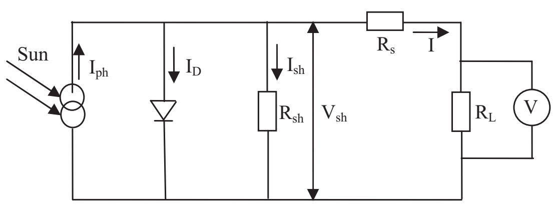


Fig. 2. The equivalent circuit for a solar cell – the one diode model.

The fill factor and the efficiency of a solar cell can be calculated by the expressions

$$FF=\frac{P_m}{I_{sc}V_{oc}}=\frac{I_mV_m}{I_{sc}V_{oc}} \tag{1}$$

$$\eta=\frac{P_m}{AI_T} \tag{2}$$

where A represents the area of solar cell and I_T the solar irradiance with spectrum AM 1.5 and $T=25\,^{\circ}$C, that is Standard Test Conditions (STC).

The solar cell electric equivalent circuits and the corresponding mathematical models take into consideration the number of diodes in the circuit. Fig. 2 presents the equivalent circuit of the one diode model which is mostly utilized to characterize the solar cells.

The mathematical model which describes the one diode model is characterized by the following equation [3]:

$$I=I_{ph}-I_o\left(e^{\frac{V+IR_s}{nV_T}}-1\right)-\frac{V+IR_s}{R_{sh}} \tag{3}$$

where V_T represents the thermal voltage, $V_T=kT/q$, k denotes the Boltzmann constant, T is the temperature of solar cell and q is the electronic charge.

In case the electronic conduction mechanisms within a solar cell are considered separately, this can be modeled by a power source and a diode in parallel for each mechanism in turn: diffusion, generation-recombination and thermionic. In this case the above mathematical model is modified by adding an exponential term for each mechanism. Thus, the two diode model, which considers the diffuse and recombination mechanisms, is described by Eq. (4) [4], while Eq. (5) [4] describes the three diode model:

$$I=I_{ph}-I_{od}\left(e^{\frac{V+IR_s}{n_dV_T}}-1\right)-I_{or}\left(e^{\frac{V+IR_s}{n_rV_T}}-1\right)-\frac{V+IR_s}{R_{sh}} \tag{4}$$

where d and r indices represent the diffusion and the generated-recombination mechanisms,

$$I=I_{ph}-I_{od}\left(e^{\frac{V+IR_s}{n_dV_T}}-1\right)-I_{or}\left(e^{\frac{V+IR_s}{n_rV_T}}-1\right)-I_{ot}\left(e^{\frac{V+IR_s}{n_tV_T}}-1\right)-\frac{V+IR_s}{R_{sh}} \tag{5}$$

where t index denotes the thermionic mechanism.

In general for the silicon solar cells it is useful to take into consideration the two diode model, but in case of thin film cells (heterojunctions) the second exponential term has a small influence, which can thus be neglected [5].

2. Methods used

The measurement of the *I–V* characteristic of the solar cells can be done in the laboratory or in natural sunlight conditions. In the former case the measurements can be performed under dark or illuminated conditions, in the latter case solar simulators being used [6–25].

Most of the methods used to determine the parameters of the solar cells use the one diode model, as the interpretation of the equation describing the mathematical model is simpler. The methods to determine the parameters aforementioned are briefly presented below.

Method 1. Chan et al. developed the analytical five point method [9]. This method uses the one diode model for solar cells and allows the determination of the following parameters: I_{ph}, I_o, n, R_s and R_{sh} (the five parameters – P) under illuminated conditions using the values of I_{sc}, V_{oc}, I_m, V_m, the slope at open-circuit point R_{so} and the slope at short-circuit point R_{sho} which are obtained from the *I–V* characteristic. The values of R_{sho} given by Eq. (6) and R_{so} by Eq. (7), can be calculated by linear fit of *I–V* characteristic around the short circuit current point and around the open circuit voltage point respectively. The shunt resistance is calculated using the following expression:

$$R_{sh}=R_{sho}=-\left(\frac{dV}{dI}\right)_{I=I_{sc}} \tag{6}$$

$$R_{so}=-\left(\frac{dV}{dI}\right)_{V=V_{oc}} \tag{7}$$

The ideality factor of the diode can be calculated by

$$n=\frac{A}{V_t(B+C)} \tag{8}$$

where A, B and C are calculated as follows:

$$A=V_m+R_{so}I_m-V_{oc} \tag{9}$$

$$B=\ln\left(I_{sc}-\frac{V_m}{R_{sh}}-I_m\right)-\ln\left(I_{sc}-\frac{V_{oc}}{R_{sh}}\right) \tag{10}$$

$$C=\frac{I_m}{I_{sc}-\frac{V_{oc}}{R_{sh}}} \tag{11}$$

The other parameters I_o, R_s and I_{ph} are obtained using the following equations:

$$I_o=\left(I_{sc}-\frac{V_{oc}}{R_{sh}}\right)\exp\left(-\frac{V_{oc}}{nV_T}\right) \tag{12}$$

$$R_s=R_{so}-\frac{nV_t}{I_o}\exp\left(-\frac{V_{oc}}{nV_T}\right) \tag{13}$$

$$I_{ph}=I_{sc}\left(1+\frac{R_s}{R_{sh}}\right)+I_o\left(\exp\left(\frac{I_{sc}R_s}{nV_T}\right)-1\right) \tag{14}$$

Method 2. Ishibashi et al. proposed a new method for the derivation of all solar cell parameters. The parameters are obtained by a single *I–V* characteristic measured under illumination conditions, using the one diode model with only one assumption, Eq. (15), which is true for the most types of solar cells [10].

$$\Delta=\exp\left(-\frac{V_{oc}-I_{sc}R_s}{nV_T}\right)\ll 1 \tag{15}$$

Using the equations obtained from Eq. (3) for the coordinates (0, I_{sc}) and (V_{oc}, 0), and the assumption Eq. (15) the following expression is obtained:

$$-\frac{dV}{dI}=\frac{nV_T}{I_{sc}-I-[V-R_s(I_{sc}-I)-nV_T]/R_{sh}}+R_s \quad (16)$$

Substituting $I=I_{sc}$ and $V=0$ into Eq. (16) the relation becomes

$$-\left(\frac{dV}{dI}\right)_{I=I_{sc}}=R_{sh}+R_s\cong R_{sh} \quad (17)$$

where $R_s \ll R_{sh}$. Ishibashi et al. introduced two temporary parameters in Eq. (16), R_{so} and n_o to determine the series resistance and the ideality factor of diode. These two terms are used in an iterative process [7]. By plotting $-dV/dI$ vs. $\{I_{sc}-I-[V-R_{os}(I_{sc}-I)-n_oV_T]/R_{sh}\}^{-1}$, n can be obtained as a slope and R_s as a y-intercept. The iterative process begins with $R_{so}=0$ and $n_o=0$ and ends when $|\delta|=0$, where δ is given by the following formula:

$$\delta=\frac{(R_s-R_{so})(I_{sc}-I)+(n-n_o)V_T}{V-R_{so}(I_{sc}-I)-n_oV_T} \quad (18)$$

Therefore, the other parameters, I_o and I_{ph} can be obtained using the following expressions:

$$I_o=\left(I_{sc}-\frac{V_{oc}-I_{sc}R_s}{R_{sh}}\right)\exp\left(-\frac{V_{oc}}{nV_T}\right) \quad (19)$$

$$I_{ph}=\frac{V_{oc}}{R_{sh}}+I_o\left(\exp\left(\frac{V_{oc}}{nV_T}\right)-1\right) \quad (20)$$

Method 3. Chegaar et al. developed a simple method to extract the following parameters of the solar cell: R_{sh}, R_s, I_o and n. The parameters are obtained under illuminated conditions using a single I–V characteristic, the one diode model, an auxiliary function $F(V)$ and a fitting routine [2]. The shunt resistance is obtained using Eq. (6). An auxiliary function is introduced by Chegaar et al. to determine the other three parameters:

$$F(V)=V-V_a\ln(I_{ph}-I) \quad (21)$$

where V_a represents an arbitrary value of the voltage. Using Eq. (3) without the last term and I instead of V, Eq. (21) becomes

$$F(I)=aI+b\ln(I_{ph}-I)+c_o \quad \text{where} \quad a=-R_s, \quad b=nV_T \quad \text{and} \quad c=-nV_TI_o \quad (22)$$

The series resistance, the ideality factor of the diode and the reverse saturation current can be determined by fitting the curve $F(I)$ vs. I. The curve is obtained by calculating $F(I)$ for each point (V, I) at a constant temperature and for a value of V_a. Chegaar et al. take into consideration integer values for V_a between 1 and 5, [2]. The photogenerated current is considered approximately equal with the short circuit current.

Method 4. The parameters of the solar cell such as R_{sh}, R_s, I_o and n can be calculated with the method developed by Tivanov et al. [11]. Considering the mathematical equation for the one diode model, which is represented by Eq. (3), approximating $I_{ph}\approx I_{sc}$ and analyzing the I–V characteristic of solar cell at a fixed level of illumination, its parameters can be determined by the following equations:

$$R_s=-\frac{1}{2}\left\{\left[(a-b)^2+\frac{2p}{I_{sc}}(a-b)+\left(\frac{V_{oc}}{I_{sc}}\right)^2\right]^{1/2}+(a+b)+\frac{V_{oc}}{I_{sc}}\right\} \quad (23)$$

$$R_{sh}=\frac{V_{oc}}{\frac{nV_T}{b+R_s}-\frac{nV_T}{a+R_s}+I_{sc}} \quad (24)$$

$$I_o=\frac{I_{sc}}{\gamma}-\frac{V_{oc}}{\gamma R_{sh}}, \quad \gamma=\exp\frac{V_{oc}}{nV_T}-1 \quad (25)$$

$$p=V_{oc}\frac{\gamma+2}{\gamma}-2nV_T, \quad a=\left(\frac{dI}{dV}\right)^{-1}_{V=0}, \quad b=\left(\frac{dI}{dV}\right)^{-1}_{I=0} \quad (26)$$

The assigned particular value of n is verified by comparison with the value obtained with the following equation:

$$n=\frac{(V_m-I_mR_s)(I_{sc}+I_o-I_m-V_m/R_{sh})}{V_T(I_m-V_m/R_{sh})} \quad (27)$$

In the particular case when $a\to-\infty$ Eqs. (23)–(25) become

$$R_s=|b|-\frac{nV_T}{I_{sc}}, \quad R_{sh}\to\infty, \quad I_o=\frac{I_{sc}}{\gamma} \quad (28)$$

Method 5. Easwarakhanthan et al. developed the vertical optimization method. The one diode model was used for solar cell. This method allows the determination of the five parameters of solar cells using the non-linear least squares optimization algorithm [12]. The modified Newton method with the Levenberg parameter is used for the algorithm. The objective function S in case of the study of a solar cell is

$$S(P)=\sum_{i=1}^{N}(I_i-I(V_i,P))^2 \quad (29)$$

where I_i, V_i are values on the I–V characteristic whose mathematical model is given by Eq. (3) and P represents the set of the five parameters. The goal is to minimize the S function.

Method 6. The electric conductance optimization method was developed by Chegaar et al. [13]. This method allows the determination of the five parameters of a solar cell using the non-linear least squares optimization algorithm considering the one diode model for the solar cell. The method is based on the modified Newton method with the Levenberg parameter used. This method considers the I–V characteristic and the slope of this curve. The objective function S_1 in case of the solar cell is

$$S_1(P)=\sum_{i=1}^{N}(G-G_i(V_i,I_i,P))^2 \quad (30)$$

where G is the conductance calculated with Eq. (31), I_i and V_i are the values on the I–V characteristic, G_i represents the computed conductance and P represents the set of the five parameters. The goal is to minimize the S_1 function.

$$G=-\frac{I_{ph}-I_o-(V+IR_s)G_{sh}+nV_TG_{sh}}{nV_T+R_s(I_{ph}-I_o-(V+IR_s)G_{sh}+nV_TG_{sh})} \quad \text{where } G_{sh}=\frac{1}{R_{sh}} \quad (31)$$

Method 7. Chegaar et al. proposed the simple conductance technique based on Werner′s method [12,13]. The five parameters can be determined using the one diode model and Eq. (3) in two steps. In the first step the shunt conductance G_{sh} is determined by simple linear fitting of the reverse bias characteristic for a large negative bias voltage. The second step consists of rewriting Eq. (3) in forward conditions for $V+R_sI \gg kT$ and calculating the conductance $G=dI/dV$:

$$\frac{G}{I_{ph}-I}=-\frac{1}{nV_T}-\frac{R_s}{nV_T}G \quad (32)$$

Using the plot of Eq. (32), the ideality factor n of the diode can be determined by the y-intercept and the series resistance R_s by the slope respectively. For the photogenerated current, it is highly acceptable to approximate $I_{ph}\approx I_{sc}$. Taking into consideration the I–V data corrected using the effect of the series resistance, I_o can be determined by the standard method based on the forward I–V data [4].

Method 8. Haouari-Merbaha et al. developed a method to determine the parameters of solar cells based on the two diode

model [15]. The I–V characteristic of a solar cell measured under illumination conditions is split in two regions by the resistive line with slope V_{oc}/I_{sc}, the first region is near the short circuit current and the second region is near the open circuit voltage. These two regions of the I–V characteristic are fitted as follows: the first region as a function of the current and the second as a function of the voltage. For the first region Eq. (4) can be modeled as Eq. (33) and for the second as Eq. (34):

$$I = I_{sc} - G_{sh}^{s} V - a_3 h^{s}(I,V) \tag{33}$$

$$V = V_{oc} - IR_s^{o} - b_3 h^{o}(I,V) \tag{34}$$

where the superscript "s" is for the first region, the superscript "o" is for the second region, $h^i(I,V)$ represents the curvature of the I–V characteristic, i can be either s or o [14]. The coefficients $(I_{sc}, G_{sh}{}^{s})$ can be obtained by fitting the first region near short circuit, with Eq. (33) and the coefficients $(V_{oc}, R_s{}^{o})$ can be obtained by fitting the second region near open circuit, with Eq. (34). The set of parameters (I_{ph}, $G_{sh}=1/R_{sh}$, I_{od}, I_{or}, R_s) can be determined by solving the system with five non-linear equations obtained for: I_{sc}, $G_{sh}{}^{s}$, V_{oc}, $R_s{}^{o}$ and the curve passes through the boundary point, which is around the maximum power point [15]. The ideality factors of the diode take the theoretical values $n_d=1$ and $n_r=2$. Solving the system starts with the set of parameters equal with zero and the iterative process is done when the parameters converge.

Method 9. The method proposed by Ortiz-Conde et al. to determine the parameters of a solar cell is based on the Co-content function CC [16]. The one diode model and Eq. (3) are used to characterize the solar cell. The I–V characteristic is obtained under illumination conditions. Using the Lambert W function and the Co-content function CC, Eq. (3) can be rewritten as

$$CC(I,V) = C_{V1}V + C_{I1}(I - I_{sc}) + C_{I1V1}V(I - I_{sc}) + C_{V2}V^2 + C_{I2}(I - I_{sc})^2 \tag{35}$$

The equation coefficients C_{V1}, C_{I1}, C_{V2} and C_{I2} can be determined through fitting Eq. (35) using the CC function. The CC function is numerically calculated from the measured data as follows:

$$CC(I,V) = \int_0^V (I - I_{sc})\,dV \tag{36}$$

Provided the equation coefficients are determined, the parameters of the solar cell can be calculated by

$$R_{sh} = \frac{1}{2C_{V2}} \tag{37}$$

$$R_s = \frac{\sqrt{1 + 16C_{V2}C_{I2}} - 1}{4C_{V2}} \tag{38}$$

$$n = \frac{C_{V1}\left(\sqrt{1 + 16C_{V2}C_{I2}} - 1\right) + 4C_{I1}C_{V2}}{4V_T C_{V2}} \tag{39}$$

$$I_{ph} = -\frac{(C_{V1} + I_{sc})\left(\sqrt{1 + 16C_{V2}C_{I2}} + 1\right)}{2} - 2C_{I1}C_{V2} \tag{40}$$

$$I_o = \frac{I - (V - IR_s)/R_{sh} + I_{ph}}{\exp((V - IR_s)/nV_T) - 1} \tag{41}$$

Method 10. Zhang et al. developed a method to determine the parameters of the solar cell based on the one diode model, the single I–V characteristic under the constant illumination level and the Lambert W function [17]. The implicit Eq. (3) can be transformed into an explicit equation with five unknown parameters I_{ph}, I_o, n, R_s and R_{sh} by using the Lambert W function. Using Eq. (3) in the particular points (0, I_{sc}) and (V_{oc}, 0) and the assumption given by Eq. (15), a simplified explicit equation can be obtained:

$$I = \frac{nV_T}{R_s}\text{Lambert } W\left[\tfrac{R_s}{nV_T}\left(I_{sc} - \tfrac{V_{oc}}{R_s + R_{sh}}\right)\exp\left(\tfrac{-V_{oc}}{nV_T}\right) x \exp\tfrac{1}{nV_T}\left(R_s I_{sc} + \tfrac{R_{sh}V}{R_s + R_{sh}}\right)\right] + \frac{V}{R_s} - I_{sc} - \frac{R_{sh}V}{R_s(R_s + R_{sh})} \tag{42}$$

It can be observed that Eq. (42) is an explicit equation and it has only three parameters n, R_s and R_{sh}. These parameters can be determined by the numerical fitting method. The initial values for these three parameters can be obtained as follows: the shunt resistance using Eq. (16) and using the linear dependency dV/dI in function of $(I_{sc} + I - V/R_{sh})^{-1}kT/q$, the series resistance and the ideality factor n of diode can be found by intercept and slope. The saturation current and the photogenerated current can be calculated using Eqs. (19) and (20).

Method 11. Garrido-Alzar developed a method to determine the solar cell parameters based on the two diode model. The method consists of solving the equation system obtained by Eq. (4) for four points from the I–V characteristic (V_i, I_i), $i=1,2,3,4$ and $n_d=1$, in the zero order approximation for n_r and R_s [18]. In this step, the following parameters can be calculated: I_{ph}, I_{od}, I_{or} and R_{sh}. To compute n_r the following equation is used:

$$n_r = \frac{V_{oc}}{V_T\left\{\ln\left[I_{or} + I_{ph} - I_{od}\left(\exp\left(\frac{V_{oc}}{V_T} - 1\right)\right) - \frac{V_{oc}}{R_{sh}}\right] - \ln I_{or}\right\}} \tag{43}$$

The series resistance is obtained using the following equation:

$$I_5 = I_{ph} - I_{od}\left(e^{\frac{V_5 + I_5R_s}{V_T}} - 1\right) - I_{or}\left(e^{\frac{V_5 + I_5R_s}{m_rV_T}} - 1\right) - \frac{V_5 + I_5R_s}{R_{sh}} \tag{44}$$

The above steps must be repeated until, for example, the value of n_r is obtained with the desired precision [18]. Here, $n_r \neq 2$ as in method 8.

Method 12. Kiran and Inan developed a method to determine the parameters of the solar cell based on the one diode model under illumination conditions [19]. They obtained an approximation equation from Eq. (3) by eliminating the saturation current and considering the shunt resistance as infinite, which is rendered as Eq. (45). With such an assumption, it is clear that the method provides results which deviate from the expected values when the cell is aged. This has a value in the field of study of the PV cell aging.

$$V = V_{oc} - IR_s + mV_T \ln\left\{\frac{I_{sc} - I}{I_{sc}} + \exp\frac{I_{sc}R_s - V_{oc}}{nV_T}\right\} \tag{45}$$

There are only three parameters R_s, n and I_{sc} in Eq. (45). These parameters can be computed by fitting the experimental data. The photogenerated current can be obtained as $I_{ph} \approx I_{sc}$. The saturation current is given by the following equation:

$$I_0 = \frac{I_{sc}}{\exp\left(\frac{V_{oc}}{nV_T}\right) - 1} \tag{46}$$

Method 13. Sellami and Bouaïcha determined the five parameters of the solar cell using the one diode model, the I–V characteristic which is measured under illumination conditions and for the fitting procedure the genetic algorithm (GA) is used [20]. The GA consists of some preliminary decisions: solution encoding, evaluation function, initial population generation, selection criterion, recombination/reproduction and termination criteria. The evaluation function used in GA, derived from Eq. (3) is

$$I(V_i, P) = I_{ph} - I_o\left(e^{\frac{V_i + IR_s}{nV_T}} - 1\right) - \frac{V_i + IR_s}{R_{sh}} \tag{47}$$

The cost function can be defined in the case of solar cells as the sum of the squared difference between the experimental and theoretical current values given by Eq. (29). In case of the genetic

algorithm, the accuracy criterion being given by the cost function, this has to be minimized. The cost function does not involve the derivatives and it is determined for each chromosome. The initial population of chromosomes IPOP can be calculated as follows [12]:

$$IPOP=(h_i-l_o)\ \text{random}\ \lfloor N_{ipop},N_{par}\rfloor+l_o \tag{48}$$

where N_{par} is the number of parameters, 5 in this case, N_{ipop} represents the number of chromosomes, h_i and l_o are the highest and the lowest values of the five parameters respectively. The selection of the family of chromosomes is made function of the cost. The genetic algorithm GA is stopped when the value of the $S(P)$ is smaller than the predefined cost minimum. The flow chart described by Sellami and Bouaïcha is presented in Fig. 3. The same method was used by Jervase et al. [21], but they determined the parameters of the solar cell for the two diode model.

Method 14. Ye et al. determined the five or seven parameters of the solar cell using the one or two diode model, the *I–V* characteristic which is measured under illuminated conditions and the particle swarm optimization algorithm (PSO) [22]. The same method is described by Qin and Kimball [23]. The PSO algorithm allows the determination of the solar cell parameters without using the differential equations. This algorithm is an iterative one, in which each particle flies in a space with a velocity, which is updated as a linear combination by the position, the inertia weight, social iteration and self cognition. The velocity and position for each particle are updated as follows:

$$v_i(k+1)=w(k)v_i(k)+c_1r_1(k)\left[p\ \text{best}_i(k)-x_i(k)\right]+c_2r_2(k)\left[g\ \text{best}_i(k)-x_i(k)\right] \tag{49}$$

$$x_i(k+1)=v_i(k+1)+x_i(k) \tag{50}$$

where x_i represents the ith particle position (each particle contains a vector with the solar cell parameters values), w is the inertia weight, v_i is the velocity of ith particle, r_1 and r_2 are the random numbers between 0 and 1, c_1 and c_2 are the acceleration constants, *p*best is the particle′s best known position, *g*best represents the best known position found by all particles [22,23]. The objective function which has to be minimized is

$$F=\sqrt{\frac{\sum_{k=1}^{N}f_k^2}{N}},\quad f_i=|I_p-I_m| \tag{51}$$

where I_p represents the predicted current, I_m represents the measured current and f_i is the fitness function for one sampled point. The iteration process is stopped when the fitness function reaches minimum conditions.

Within this concept of solar cell analysis, Sandrolini et al. determined the seven parameters of a solar cell using the two diode model, the *I–V* characteristic which is measured under illuminated conditions and the PSO algorithm and cluster analysis handled together [24].

Method 15. Stutenbaeumer and Mesfin used the non-linear curve fitting to determine the six parameters of the solar cell using the simplified two diode model of a solar cell under dark conditions [25]:

$$I=I_{od}\left(e^{\frac{V}{n_dV_T}}-1\right)+I_{or}\left(e^{\frac{V}{n_rV_T}}-1\right)+\frac{V}{R_{sh}} \tag{52}$$

The simplified two diode model of the solar cell can be obtained for small values of R_s. In this case, the approximation $V \gg IR_s$ holds.

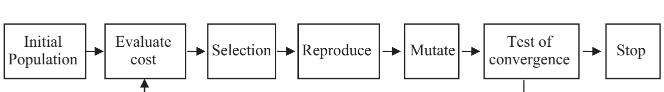


Fig. 3. GA flow chart.

The *I–V* characteristic is measured under both illumination and dark conditions. In order to reduce the number of fitting parameters the ideality factor of diode n_d takes the value 1. The series resistance is calculated as follows:

$$R_s=\frac{V_{sc}-V_{oc}}{I_{sc}} \tag{53}$$

where V_{sc} represents the necessary voltage in dark condition to obtain the same short circuit current as in illumination conditions.

The fitting procedure to determine the parameters uses the non-linear fitting algorithm developed by Levenberg–Marguardt which is implemented in Origin.

Method 16. Kaminski et al. determined the following parameters of the solar cell I_{od}, I_{or}, n_d, n_r, R_s and R_{sh} using the two diode model in dark conditions [26,27]. The *I–V* characteristic of the solar cell in dark conditions is analyzed on two regions: the first represents the higher part where the series resistance and the diffusion mechanism are important and the second represents the lower part where the shunt resistance and the recombination mechanism are important. The first part is used to determine the following parameters: I_{od}, n_d and R_s. The series resistance and the ideality factor of the diode can be determined using the linear regression of Eq., (54).

$$y=\frac{1}{n_dV_T}(-R_s+x),\quad y=\frac{\ln(I/I_1)}{I-I_1},\quad x=\frac{V-V_1}{I-I_1} \tag{54}$$

where (V_1,I_1) is a point on the first part of the solar cell *I–V* characteristic. If the correlation coefficient is not good, then the value of I_1 must be raised. The saturation current, I_o, can be estimated by plotting $\ln I$ in function of $V-IR_s$. The second part of the characteristic curve is used to determine the following parameters: I_{or}, n_r and R_{sh}. The linear part of the lower part of *I–V* characteristic is fitted by the least square method using Eq. (55).

$$I=I_{or}\left[e^{\frac{V-IR_s}{n_rV_T}}-1\right] \tag{55}$$

The shunt resistance is calculated then by Eq. (56).

$$R_{sh}=\left[\left(\frac{dI}{dV}\right)_{I=I_{sc}}-\frac{I_{or}}{n_rV_T}-\frac{I_{or}}{n_rV_T}\right]^{-1} \tag{56}$$

Method 17. Arcipiani developed the generalized area method [28]. This method allows the determination of the following solar cell parameters: the ideality factor of diode, the series and shunt resistance. The method consists of calculating the area between the OV and OI axes and the *I–V* characteristic of solar cell, Eq. (57). The one diode model was used for the solar cell, using the following expression:

$$A=(I_{ph}+I_o)(V_{oc}-rI_{sc})r+I_{sc}(1+gr)\left(\frac{rI_{sc}}{2}-V_Tn\right)+V_{oc}g\left(V_Tn-\frac{V_{oc}}{2}\right) \tag{57}$$

where $r=R_s$ and $g=R_{sh}$. Taking into consideration the following approximations $gr \ll 1$, $I_o \ll I_{ph}$ and $I_{sc}\approx I_{ph}$ which are generally accepted [29], Eq. (57) becomes

$$y=\left(\frac{I_{sc}}{2V_{oc}}\right)r+\left(\frac{1}{V_{oc}}\right)V_Tn+\left(\frac{V_{oc}}{2I_{sc}}\right)g-\left(\frac{1}{I_{sc}}\right)V_Tgn,\quad y=\frac{I_{sc}V_{oc}-A}{I_{sc}V_{oc}} \tag{58}$$

Eq. (58) contains three unknown parameters of the solar cell, r, g and n. To determine these parameters Eq. (58) should be rewritten, taking *I–V* at three different illumination levels. Then the resulting non-linear system of equations is solved.

Method 18. The method developed by Jia and Anderson allows the determination of the series resistance and the ideality factor of

diode [30]. In this method n is considered variable on the I–V characteristic, thus $n=1$ at V_{oc} and $n = 2$ at I_{sc}. The one diode model is used and the solar cell is illuminated. The series resistance can be calculated with Eq. (59) which is obtained using the following approximations: $I_{ph} \approx I_{sc}$, R_{sh} is infinite and $I_{sc} \gg I_o$.

$$R_s = \frac{V_m\,(1/V_T)(I_{sc}-I_m)\{V_{oc}+V_T\,\ln[1-(I_m/I_{sc})]\}-I_m}{I_m\,(1/V_T)(I_{sc}-I_m)\{V_{oc}+V_T\,\ln[1-(I_m/I_{sc})]\}+I_m} \tag{59}$$

The value of the ideality factor of the diode at maximum power point can be calculated as follows:

$$n=(V_m+I_mR_s)/\left(V_{oc}+V_T\,\ln\frac{I_{sc}-I_m}{I_{sc}}\right) \tag{60}$$

Method 19. The integral method was developed by Ortiz-Conde et al. [31] and Kaminski et al. improved this method [26]. The series resistance and the ideality factor of the diode can be obtained under dark conditions through the linear regression of Eq. (62). This equation is obtained from Eq. (61) through integration. The one diode model was used for the solar cell and the shunt resistance is considered infinite.

$$I=I_o\left(e^{\frac{V-IR_s}{nV_T}}-1\right) \tag{61}$$

$$y=nV_T+R_sx\,,\quad x=\tfrac{I+I_1}{2},\quad y=\tfrac{1}{I-I_1}\int_{V_1}^{V} IdV \tag{62}$$

where (V_1,I_1) is a point of the solar cell I–V characteristic and I is the dark current. The integral can be solved using the means of trapezoidal method.

Method 20. El-Adawi1 and Al-Nuaim proposed a method to determine the series and shut resistances using the one diode model [32]. The series resistance can be estimated by using Eq. (3), with the approximations shown in Eq. (63) and by choosing two points around the knee of I–V characteristic of solar cell (V_i, I_i), $i=1,2$.

$$I_oR_{sh}e^{\frac{V+IR_s}{nV_T}} \gg V\,,\quad \tfrac{R_sI_i}{R_{sh}}<I_{sc}+I_o-I_i, i=1,2,\quad I_{sc} \gg I_o,\quad I_{sc}\approx I_{ph} \tag{63}$$

$$R_s=\frac{nV_T}{I_2-I_1}\ln\frac{I_{sc}-I_2}{I_{sc}-I_1}-\frac{V_2-V_1}{I_2-I_1} \tag{64}$$

The shunt resistance can be obtained by the following equation:

$$\frac{R_{sh}+R_s}{R_{sh}(I_{sc}-I_1)-I_1R_s}=\frac{V_1-R_s}{nV_TI_1} \tag{65}$$

Thongprona et al. had used the same method before, but for both dark and illuminated conditions [33].

Method 21. The ideality factor of the diode and the reverse current can be determined by using the semi-logarithmic $I_{sc}-V_{oc}$ characteristic, as in the equation below. The short circuit current and the open circuit voltage must be determined for different levels of illumination. In this method, the one diode model is used with the following approximations:

$$R_{sh}\to\infty,\quad I_{sc}\approx I_{ph},\quad e^{\frac{V_{oc}}{nV_T}}\gg 1 \tag{66}$$

Under these conditions, Eq. (3) becomes

$$\ln I_{sc} = \ln I_o+\frac{1}{nV_T}V_{oc} \tag{67}$$

The ideality factor of the diode can be calculated from the slope of the semi-logarithmic characteristic and the saturation current is calculated using the intercept of the characteristic on Y-axis.

Priyanka et al. improved this method by taking into consideration the value of the shunt resistance [34]. Eq. (67) becomes

$$\ln\left(I_{sc}-\frac{V_{oc}}{R_{sh}}\right) = \ln I_o+\frac{1}{nV_T}V_{oc} \tag{68}$$

Method 22. The method developed by Signal allows the determination of the series resistance and the ideality factor of diode using the one diode model for one level of illumination [35]. The shunt resistance for this method is considered infinite. The author developed analytical relations for P_m, I_m, V_m and FF in function of n and R_s. The values for n were chosen 1 or 2. The series resistance was considered ideal (R_s=0) or real ($R_s \neq 0$). For two values of n and R_s, ΔFF and $\Delta(V_m/V_{oc})$ were calculated. If n is not equal the correct value of n, the value of the series resistance obtained from ΔFF differs from that obtained from $\Delta(V_m/V_{oc})$. The series resistance and the ideality factor of the diode are found by varying the value of n until the two values of R_s obtained from ΔFF and $\Delta(V_m/V_{oc})$ are almost equal.

Method 23. The series and shunt resistance can be determined using the one diode model and the I–V characteristic of a solar cell in the third and fourth quadrants under illumination conditions. This method was developed by Priyanka et al. [34]. The series resistance can be calculated using the following equation:

$$R_s=\frac{nV_T}{I_f}\ln\left[\frac{I_rR-(V_r+V_f+I_fR)}{I_oR}\right]-\frac{V_f}{I_f} \tag{69}$$

where $R=R_s+R_{sh}$, I_f, V_f represent I, V in the fourth quadrant and I_r, V_r represent I, V in the third quadrant. The shunt resistance can be determined using the Eq. (6) and by making the approximation $R_s \ll R$, R is determined. The ideality factor of the diode and the saturation current must be previously determined using method 21.

The series resistance can be obtained more accurately using Eq. (70) by iteration. The first value of the series resistance in iterative process is given from Eq. (69).

$$R_s=\frac{nV_T}{I_f}\ln\left[\frac{I_rR-(V_r+V_f+I_fR)}{I_o(R-R_s)}\right]-\frac{V_f}{I_f} \tag{70}$$

The values for I_r and I_f should be chosen so that

$$I_rR-(V_r+V_f+I_fR)>0 \tag{71}$$

Method 24. Bowden and Rohatgi developed a method which allows the determination of the two parameters of the solar cell, n and R_s [36]. In this method, two I–V characteristics are used, one measured for one sun illumination and the other measured for 0.1 sun illumination or in the ideal case, at such an illumination level that the short circuit current of the solar cell equals the difference $I_{sc,1}-I_{m,1}$. The series resistance can be calculated using

$$R_s=\frac{V_{oc,0,1}-V_{m,1}}{I_{sc},1-I_{sc,0,1}} \tag{72}$$

where the pair ($V_{m,1}$, $I_{sc,1}$) is obtained from the I–V characteristic measured for one sun illumination and the pair ($V_{oc,0,1}$, $I_{sc,0,1}$) is obtained from the I–V characteristic measured for 0.1 sun illumination. The ideality factor of diode can be calculated using

$$n=\frac{V_{oc,1}-V_{oc,0,1}}{\ln(I_{sc,1}/I_{sc,0,1})}\frac{1}{V_T} \tag{73}$$

Method 25. The series resistance can be determined by the two characteristics method which was suggested by Swanson [37], described by Wolf and Rauschenbach [38] and reiterated by Bashahu and Habyarimana [39]. In this method the I–V characteristic of a solar cell is measured at the same temperature for two

levels of illumination. The series resistance can be calculated using the following equation:

$$R_s = \frac{\Delta V}{\Delta I_{sc}} = \frac{V_2 - V_1}{I_1 - I_2} \tag{74}$$

where the points (V_i, I_i), $i=1,2$ are obtained from the *I–V* characteristics, considering the value of ΔI so that the parallel drawn through I_1 to the Ox axis intersects the characteristic for the highest illumination level just a little below the maximum power point, see Fig. 4.

Pysch et al. proposed a modification where at least three *I–V* characteristics were used to determine the series resistance. These *I–V* characteristics can be obtained for three levels of illumination: one sun, slightly above and slightly below one sun [40].

Method 26. Araújo and Sánchez developed the area method to determine the series resistance of a solar cell [29]. In this method the one diode model was used, Eq. (3). R_{sh} is considered infinite and the ideality factor of the diode has the value equal to one. In this case, the series resistance can be calculated as follows:

$$R_s = 2\left(\frac{V_{oc}}{I_{sc}} - \frac{A}{I_{sc}^2} - \frac{V_T}{I_{sc}}\right) \tag{75}$$

where A represents the area between the *I–V* characteristic curve and the *I* and *V* axes.

Method 27. Cape et al. developed the flash lamp method [41]. This method allows the determination of the series resistance using Eq. (76). The one diode model was used and R_{sh} is considered infinite.

$$R_s = R_L\left(\frac{V_{oc}}{V_L} - 1\right) \tag{76}$$

where R_L represents the load resistance and V_L denotes the voltage across the load resistance. This method uses two very short pulses with duration of 1 ms, to determine V_{oc} and V_L. The open circuit voltage is determined by using the first light pulse. The voltage across the load resistance, which was previously measured with precision, is determined using the second light pulse.

Method 28. The maximum power point method which allows the determination of the series resistance was developed by Picciano [42,43]. The method uses the one diode model and the *I–V* characteristic is measured for a single illumination level. The shut resistance is considered infinite and the ideality factor of the diode has a constant value over the entire *I–V* characteristic.

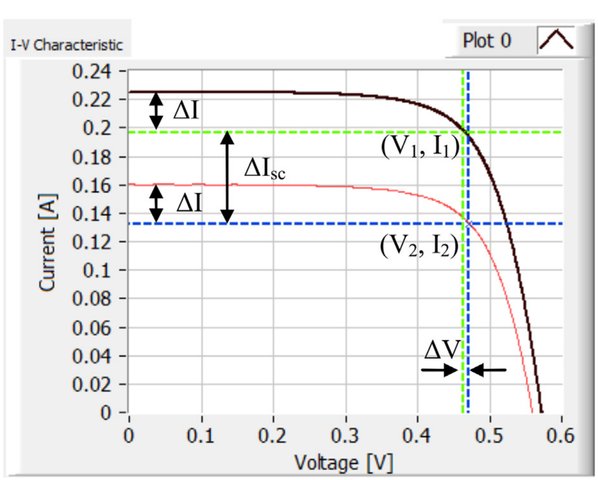


Fig. 4. The method with two *I–V* characteristics for the determination of solar cell series resistance.

The series resistance can be determined as follows:

$$R_s = \frac{V_m}{I_m} - \frac{1}{B(I_{sc} - I_m)} \tag{77}$$

where

$$B = \frac{[I_m/(I_{sc} - I_m)] + \ln[(I_{sc} - I_m)/I_{sc}]}{2V_m - V_{oc}} \tag{78}$$

Method 29. The method developed by Cotfas et al. allows the determination of the series resistance using the one diode model [44]. This method uses two *I–V* characteristics – one is measured and the other is ideal, Fig. 5. For the ideal case the *I–V* characteristic can be calculated with $n=1$ or with the real values for n and I_o obtained with method 21. The series resistance can be calculated with Eq. (79).

$$R_s = \frac{\Delta V}{I_m} = \frac{V_{ideal} - V_m}{I_m} \tag{79}$$

where V_{ideal} is obtained on the ideal *I–V* characteristic for I_m.

Method 30. Agarwal et al. developed a method which allows the determination of the series resistance using the one diode model and the variation of photogenerated current function of the levels of illumination [45]. The shunt resistance for this method is considered infinite. The short circuit current can be approximated with the photogenerated current for low illumination levels, smaller than 750 W/m^2. Under low illumination levels, it shows linear dependency vs. the illuminations levels. For illumination levels higher than 750 W/m^2 the dependency is under linear. The difference between the photogenerated current, by projecting the tangent of the I_{sc} at low I_t, with the I_{sc} curve obtained at normal I_t, becomes significant. The series resistance can be found using the slope of the semi-logarithmical dependence $\ln(I_{ph} - I_{sc})$ vs. I_{sc} which is linear for illumination levels above 750 W/m^2:

$$\ln\left(\frac{I_{ph} - I_{sc}}{I_o}\right) = \frac{R_s I_{sc}}{nV_T} \tag{80}$$

where n and I_o can be calculated using method 21 or can be approximated with values from ideal cases.

Method 31. The series resistance of solar cells can be determined using the method developed by Polman et al. [46]. This method uses the two diode model for the solar cell description. The shunt resistance and the ideality factor of diode are taken into consideration. Using Eq. (81), the series resistance can be calculated as the average between the values obtained when n takes the

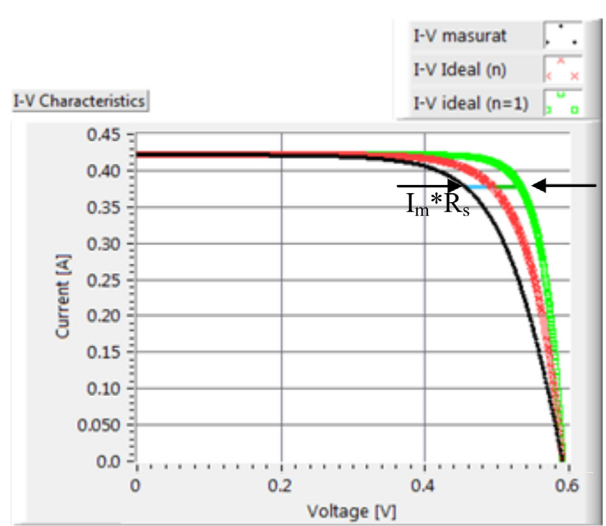


Fig. 5. The Cotfas method.

values 1 and 2.

$$R_s = -\left(\left(\frac{\partial I}{\partial V}\right)_{V=V_{oc}}\right)^{-1} - \left(\frac{1}{nV_T}I_{ph}\right)^{-1} \tag{81}$$

where $(\partial I/\partial V)_{V=V_{oc}}$ is obtained from the slope of the linear fiting of a few points around $V=V_{oc}$.

Method 32. The method proposed by Cowley and Sze to determine the series resistance consists of measuring the semi-logarithmical I–V characteristic under dark conditions and using the one diode model. The series resistance can be calculated using the gap value on the V axis, between the semi logarithmical I–V characteristic and the diffusion line [39,47].

Method 33. The method allows the determination of the series resistance of the solar cells using both measurements under both dark and illumination conditions. Aberle et al. [48] proposed the determination of the series resistance using Eq. (82):

$$R_s = \frac{\Delta V}{I_m} = \frac{V_{dark,m} - V_m}{I_m} \tag{82}$$

where $V_{dark,m}$ represents the voltage measured in dark conditions, corresponding to the current I_m measured in illumination conditions. Because the effect of dark series resistance was neglected, the error can be larger than 5%. The series resistance is calculated with the corrected equation [49] in order to minimize the errors:

$$R_s = \frac{V_{dark,m} - V_m - (I_{sc} - I_m)R_{s,dark}}{I_m} \tag{83}$$

where $R_{s,dark}$ can be calculated using Eq. (53).

Method 34. The ideality factor of the diode can be found using the analytical method developed by Bayhan and Kavasogl [50]. In this case the measurements are performed under dark conditions; the authors used the one diode model for the solar cell description and the Lambert W-function. The value of n is calculated for two regions of I–V characteristic measured under dark conditions. The first region is for the voltage interval (0.2, 0.6) and the second region is for the voltage interval (0.6, 0.8).

3. Results and discussion

This article outlines, discusses and compares a number of 34 theoretical and experimental approaches in order to determine the important dc parameters of solar cells, like R_s, R_{sh}, n, I_o etc. The analysis of the I–V characteristic is an important tool for the determination of the above quantities and it can be measured under both illumination and darkness conditions. Most methods use the I–V characteristic obtained under illumination conditions because these are real operating conditions for a solar cell. The methods that use the dark measurements are few, for example methods 14, 15, 16, 32 and 34. There is, also, a method which uses both the dark conditions and the illumination conditions, namely method 33 developed by Aberle et al.

The equation which mathematically describes the behavior of solar cells depends on the model chosen for the solar cell. The most widely used model is the one diode model because it is the simplest and describes sufficiently well the characteristic of most solar cells behavior, as it can be seen for all methods except the methods 8, 11, 15, 16 and 31.

The first sixteen methods presented in this paper allow the determination of all the parameters: I_{ph}, I_o, R_s, R_{sh} and n. The values of I_{sc}, V_{oc}, P_m and implicitly V_m and I_m can be determined from the experimental data [10]. Two or more parameters of a solar cell are determined using methods 17–24. The last nine methods allow for the determination of one parameter, especially the series resistance which is the mostly tried parameter for solar cells.

Most of the methods which allow the determination of all the parameters use the least-squares numerical techniques. Eqs. (3) and (4) are implicit equations. The non-linear fitting procedure becomes complicated. Eq. (3) with the approximation $R_sI \ll V$ becomes an explicit equation and the fitting procedure becomes simpler. The above approximation holds for a solar cell with small area which implies that the current is small or for low level illuminations. Using the Lambert W-function, Eq. (3) becomes an explicit equation $I=I(V)$ [51] and the fitting procedure simplifies the approach. Moreover, using the assumption given by Eq. (15), the explicit equation $I=I(V)$ has only three fitting parameters. The extracted process is easier using the consecrated software such as Matlab, Mathematica and others. In Matlab only a few lines of code are necessary [17].

The accuracy of the fitting procedure depends on the following factors: the choice of the fitting algorithm, especially on the initial values of the fitting parameters and the confidence interval. Development of the generic algorithm and the particle swarm optimization may improve the accuracy of the solar cell parameter extraction. A high advantage of the method 14 in comparison with the fitting methods is that even without very good choice of the values of the initial fitting parameters, the final results are very good and the errors are very small in comparison to other experimental errors like those of methods 25, 26 etc. In method 10 the initial values of the fitting parameters are firstly calculated, leading to improvements of the results obtained by the fitting process.

To solve the statistical instability in the fitting algorithm and I–V characteristic in concentrator solar cells, Araki and Yamaguchi proposed a new mathematical model which describes the solar cell behavior:

$$I = I_{ph} - I_o\left(e^{\frac{V+IR_s}{nV_T}} - 1\right) - \frac{V+IR_s}{R_{sh}} + \varepsilon \tag{84}$$

where ε is an error term distributed through a Gaussian pdf centered at zero [52].

The area method and the generalized area method introduce a significant uncertainty brought in through the area limited between the two axes and the I–V characteristic. Sometimes, the result for R_s comes out negative [39].

The methods which use few approximations, such as the methods 10, 13 and 14 have to be applied to obtain good values for the solar cell parameters. The methods in which the ideality factor of diode is given the value equal with 1 and the shunt resistance is considered infinite must be used carefully. Method 29 shows how the value of the series resistance changes when the value of n takes the real value or the theoretical value ($n=1$).

The solar cell parameters such as: R_s, n, R_{sh} and I_o depend on the irradiance levels [17,40,44,53]. Therefore the methods 17, 21 and 25 which used two or three I–V characteristics obtained for different levels of illumination, may be used carefully. The two characteristics method 25 can be improved using three or more I–V characteristics and R_s can be calculated from the inverted slope of the linear dependency of the (V_i, I_i), $i=1,2,3,\ldots$

The series resistance obtained in dark conditions is underestimated. The series resistance is higher due to the larger lateral electron flow in the emitter under illuminated conditions, the normal operating mode for solar cells.

4. Conclusions

In this review paper 34 methods developed over the past 35 years to determine the main electric parameters of a solar cell were critically presented, assessed and discussed. The main parameters in concern are, the reverse diode saturation current, I_o, the ideality factor n of diode, the series resistance, R_s, the shunt resistance, R_{sh}, and the photocurrent, I_{ph}. The methods outlined

fall into three main groups. The first group includes the methods which are based in the theoretical analysis of the *I–V* curve based on techniques which range from simple regression, to non-linear regression, stochastic process and fitting based on genetic functions. This family of approaches may provide the values of all the above basic solar cell parameters which play the central role to the solar cell performance investigations. The second group includes methods which succeed in providing the values of most of the important parameters, as the ones above, by dealing with graphical analysis of the *I–V* measured in various illumination conditions, either at transient or at steady state. The third group of methods uses both sophisticated theoretical analysis of the *I–V* characteristic based on the one or two diode models and graphical analysis of the *I–V* curves.

These methods are deployed in such a way that they may be effectively combined in the most efficient way as to provide the values of the above five electric parameters of a solar cell. As result of the assessment of the 34 methods outlined in this paper, the researcher may choose, according to the experimental set up and the tools possessed, some of the inter-related approaches outlined above, in order to get a set of values concerning the above solar cell parameters useful for further investigation.

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